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Abstract

We have demonstrated a system for the temporal expansion of arbitrarily shaped ultrafast optical waveforms based on the principle of temporal imaging. This system has demonstrated 103x magnification of an input signal with 300 fs resolution, thus allowing ultrafast phenomena to be recorded with slower conventional technology. The physics of temporal imaging work on a single shot basis, thus it is expected that this technology will lead to a new class of single transient recorders with ultrafast resolution.

Summary

Conventional technologies for recording single transient phenomena with ultrafast resolution have limitations on the total length of time and the complexity of the signals that can be recorded. We have demonstrated a new approach to making these measurements based on the principle of temporal imaging,[1] whereby an arbitrarily shaped input signal is expanded in time before recording with conventional technology, thus the name "time microscope."

Temporal imaging is based on an analogy that exists between the components of an imaging system in space and their counterparts in the time domain. Group delay dispersion (GDD) in the input, ϕ_1'', and the output, ϕ_2'', of the system perform the role in the time domain that diffraction does in space. Imparting a quadratic temporal phase (or linear frequency chirp $d\omega/d\tau$) performs the role of the lens. The strength of this phase modulation is characterized by a focal GDD, $\phi_f'' = -(d\omega/d\tau)^{-1}$, the amount of GDD required to remove the imparted phase profile. When these processes are combined in the proper balance to satisfy a temporal imaging condition (1), a temporally scaled replica of the input waveform is created with the magnification given by (2).

$$\frac{1}{\phi_1''} + \frac{1}{\phi_2''} = \frac{1}{\phi_f''} \qquad (1)$$

$$M = -\frac{\phi_2''}{\phi_1''} \qquad (2)$$

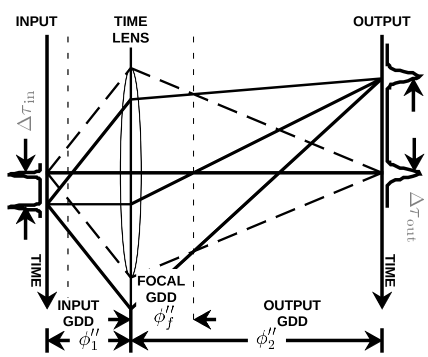

Fig. 1. A temporal ray diagram showing a two pulse sequence being expanded in time. For clarity the figure shows a system with magnification $M = -3$ whereas our experiment was constructed for $M = +100$.

We may extend this analogy and draw a ray diagram[2] of a temporal imaging system as shown in Fig. 1. For clarity the figure is drawn for the case of $M = -3$. It shows a two pulse sequence at the input of the system. The rays depict the path of particular spectral components of the input pulses as they spread in time while propagating through the input dispersion. The phase modulation process of the time lens frequency shifts each ray causing them to appear bent in Fig. 1. After further GDD the rays focus at the output creating the temporally scaled image.

The resolution of the temporal imaging system is inversely proportional to the bandwidth that is imparted by the modulation process.[1] An up-conversion temporal imaging system[3] utilizes the broad bandwidth available from ultrashort light pulses to create a "fast" lens. In our system (Fig. 2) an 87 fs (5.0 THz) pulse from a Kerr-lens modelocked Ti:Sapphire laser was dispersed in a multipass grating pair dispersive delay line,[4] generating a linearly chirped pump pulse with an amplitude and phase profile required for a time lens. These characteristics are then imparted to the dispersed input signal through noncollinear sum-frequency generation in a 500 μm thick BBO crystal.

The input and output GDD for this system was also realized with multipass grating dispersive delay lines.[4,5] Unlike spatial imaging systems where the sign of diffraction is always the same, temporal systems have the added flexibility that GDD can be positive or negative. This allows systems to be designed for either positive or negative magnification with only a single time lens. We have constructed a system for a magnification of $M = +100$ using a time lens with focal GDD $\phi''_f = +0.17784$ ps^2, and input and output GDD of $\phi''_1 = +0.17606$ ps^2, and $\phi''_2 = -17.606$ ps^2, as shown schematically in Fig. 2.

The input waveform was generated by propagating an 87 fs pulse through a Michelson interferometer. When the delay between the two arms, $\Delta\tau_{\rm in}$, is large compared to the input pulsewidth, a simple two pulse input pattern is generated. A series of temporal images, shown in Fig. 3, were recorded with a 40 GHz photodiode and sampling oscilloscope. Between each measurement the delay of pulse #2 was increased by $100.0 \pm 0.1\mu$m or 667 fs round trip. The right vertical axis in Fig. 3 is the input delay of the #2 pulse corresponding to each output trace and the bottom axis is the actual photodiode signal time scale. A linear fit to the output vs. input time of pulse #2 gives a magnification of $M = +103$ with an error of 73 fs rms referred to the input. The top scale in Fig. 3 is an equivalent input timescale found by dividing the output time by the measured magnification.

The resolution and fidelity of the total system not only depends on the quality of the imaging system but also on the final recording device. It should be noted that the impulse response of the photodiode is 12.5 ps FWHM, followed by some ringing. It is this photodiode ringing that is the dominant aberration in the total measurement system, **not** aberrations in the temporal imaging system itself. From a convolution of the ideal image, the ideal impulse response of the imaging system, and the measured impulse response of the photodiode, a 17.8 ps output pulse width was expected. The average measured width of pulse #2 in the images is 18.3 ps.

Temporal images were also recorded in 100 fs delay steps near $\Delta\tau_{\rm in} = 0$ fs. For delays as short as $\Delta\tau_{\rm in} = 300$ fs two pulses are still clearly resolved in the temporal image. When the input delay is smaller the interference of the input pulses leave what is resolvable open to interpretation.

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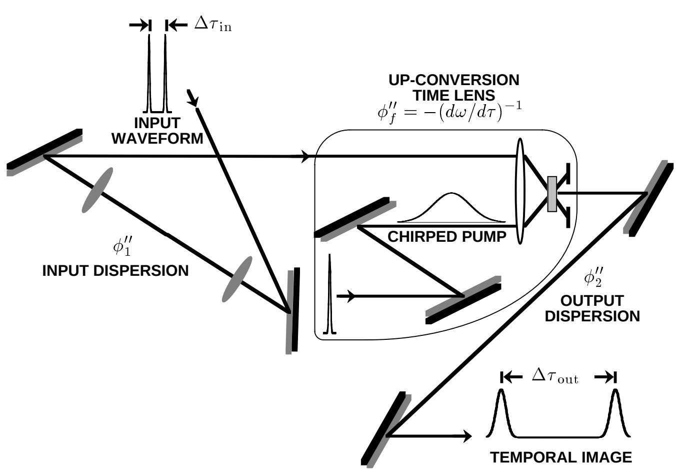

Fig. 2. An up-conversion time microscope with positive magnification. The input and output dispersions are constructed with grating pair dispersive delay lines. The time lens is produced by sum-frequency generation with a chirped pump pulse.

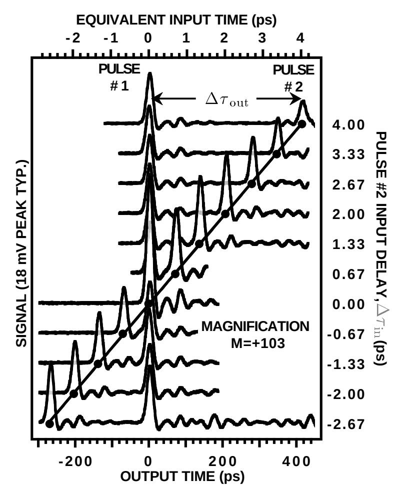

Fig. 3. A series of temporal images measured with 667 fs steps in the input delay of Pulse #2, $\Delta\tau_{\rm in}$. The corresponding output delay, $\Delta\tau_{\rm out}$, changed by 68.7 ps, indicating a magnification of M=+103.

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